NASA-STD-3001 Technical Brief

Habitable Atmosphere

OCHMO-TB-003

Executive Summary

Space is characterized by hostile conditions including variable pressure conditions, changing temperature and humidity, and the lack of a survivable atmosphere. Spaceflight vehicle designers must develop life support systems that provide a safe and comfortable living environment, facilitate safe extravehicular activities, adapt to changing environments (including vehicles, rovers, and suits), and maintain the integrity of the space vehicle. In addition to vehicle design, the crew must be protected from conditions induced by atmospheric changes including inadequate oxygen supply (hypoxia or hyperoxia) and pressure changes that can cause pressure-related illnesses or barotrauma as described in this technical brief.

Relevant Technical Requirements

NASA-STD-3001 Volume 1, Rev B

[V1 3003] In-Mission Preventive Health Care
[V1 3004] In-Mission Medical Care

NASA-STD-3001 Volume 2, Rev C

[V2 6001] Trend Analysis of Environmental and Suit Data
[V2 6002] Inert Diluent Gas
[V2 6003] 02 Partial Pressure Range for Crew Exposure
[V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure
[V2 6007] Rate of Pressure Change
[V2 6008] Decompression Sickness (DCS) Risk Identification
[V2 6009] Decompression Sickness Treatment Capability
[V2 6017] Atmospheric Control
[V1 6020] Atmospheric Data Recording
[V1 6021] Atmospheric Data Displaying
[V1 6022] Atmospheric Monitoring and Alerting Parameters
[V1 6108] Off-Nominal Vehicle/Habitat Atmospheric Ventilation
[V1 6150] Barotrauma Prevention
[V1 7041] Environmental Control
[V2 9053] Protective Equipment
[V2 11032] LEA Suited Decompression Sickness Prevention Capability
[V2 11100] Pressure Suits for Protection from Cabin Depressurization

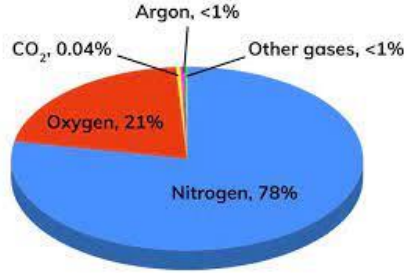
Background

Air Constituents

A safe breathable atmosphere is critical to crewmember health and performance. A spacecraft must provide and maintain atmospheric constituents in the proper quantities and pressure environments to mitigate risks of fire, decompression sickness (DCS), and hypoxia while maintaining performance and operational requirements during spaceflight. Extra vehicular activities (EVAs) and crewmember excursions on lunar and planetary surfaces must also be considered.

Sea Level Air Composition

- 78.08% Nitrogen
- 20.95% Oxygen
- 0.93% Argon
- 0.038% Carbon Dioxide and other gases



Source: NASA

Crewmember Consideration

Atmospheric concerns when considering human health must ensure optimal oxygen, diluent gas, and pressure environment to avoid Hypoxia, Hyperoxia, Decompression Sickness (DCS), and Barotrauma which will be covered in detail later in this Technical Brief.

Diluent Gas is a physiologically inert gas. Nitrogen is the most used diluent gas of the air constituents with Argon and other trace constituents used occasionally. The function of diluent gas is to prevent excessive levels of oxygen absorption during prolonged exposures which could increase risk of lung impairment (Atelectasis). Diluent gases are also used to reduce the atmosphere ignition/flammability threshold. (See next page for related technical requirement).

Gas Laws – Atmospheric gas behavior is best explained by gas laws that govern it.
Ideal Gas Law describes relation between Pressure(P), Volume (V), and Temperature (T) of gas. $PV=nRT$
Boyles Law describes how gas volumes vary with changes in ambient pressure. $P2/P1=V1/V2$
Charles Law relates the volume and temperature of gas held at constant pressure. $V1/V2=T1/T2$
Daltons Law describes the relationship of partial pressures in mixture of gasses. $PT=P1+P2+\ldots Px$

Atmosphere Measurement

- Total pressure includes all air components $PT=PO2+PN+\ldots$ (see Daltons law above).
- Partial Pressure (pp) is a measure of the proportion of a single gas in a mixture of gases. (i.e., ppO2, ppCO2, ppN).
- Pressure Units: Total pressure can be expressed as: ATA (atmosphere absolute), mmHg (millimeters of mercury), psia (pounds per square inch), or absolute kPa (kilopascals).

Sea Level Total Air Pressure
1 ATM=760 mmHg=14.7psia=101.3 kPa

Standard Sea-Level Atmosphere

Parameter	Standard Sea-Level Atmosphere Values			
	kPa	psi	mmHg	% by volume
Total Pressure	101	14.7	760	100
Oxygen Partial Pressure	21.2	3.07	159	20.9
Nitrogen Partial Pressure	79.2	11.5	594	78.1
Ar Partial Pressure	0.90	0.13	7	0.93
Water Vapor Partial Pressure	1.03	0.15	7.6	1.00
CO_2 Partial Pressure	0.03	0.01	0.3	0.03

Source NASA HIDH

Application

Total Pressure Limits

Total atmospheric pressure is the pressure of the surrounding gases applied equally to the entire body. When designing a vehicle, total pressure must prevent the vaporization of body fluids (ebullism), which occurs at 6.27 kPa (0.91 psi, 47.0 mmHg) at 37°C (98.6°F) (normal body temperature) while not exceeding human physiologic tolerances[38].

Spacecraft Cabin Design Total Pressure Considerations

- Ensure Oxygen is at suitable partial pressure for metabolic use and low enough to prevent O_2 toxicity.
- Maintain the ratio of cabin to spacesuit pressure to minimize the risk of DCS.
- Maintain cabin pressure, gas density for cooling, and gas concentration minimizing flammability.
- Provide physiologically inert gas at low pressures to prevent atelectasis for durations >2 weeks.
- All other atmospheric constituents must be inert or of low enough concentration to preclude toxic effects.
- The breathing atmosphere must have minimal flame or explosive hazard. *Source: HIDH*
- Crew are trained to don oxygen masks anytime symptoms of hypoxia are experienced.
- Crewmember pure O_2 exposure duration is limited to prevent risk of lung damage (atelectasis).
- Supplemental O_2 may be insufficient to maintain tissue oxygenation with pressures <130mmHg/2.5psia, 41,500 ft EAA.

[V2 6002] Inert Diluent Gas Cabin atmospheric composition **shall** contain at least 30% diluent gas (assuming balance oxygen). *From: NASA-STD-3001 Volume 2, Rev C*

Factoring the diluent gas standard of 30%, the following technical requirement applies:

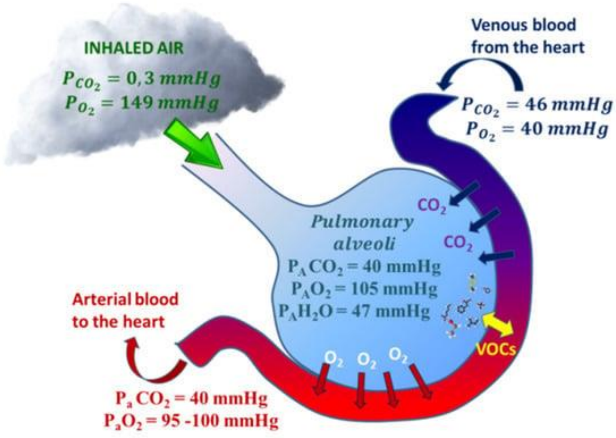
[V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure The system **shall** maintain the pressure to which the crew is exposed to between 34.5 kPa < pressure ≤ 103 kPa (5.0 psia < pressure ≤ 15.0 psia) for indefinite human exposure without measurable impairments to health or performance. *NASA-STD-3001 Volume 2, Rev D**

Designers and physiologists have to evaluate and trade off the various atmospheric combinations. A low total pressure is desirable because it allows simple transfer to a low-pressure EVA suit. (Low pressure EVA suits are less stiff and allow greater range of motion). Low total pressure requires a higher percentage of oxygen in the atmosphere to provide an acceptable PIO_2. Oxygen-rich atmospheres, however, present safety hazards because of their ability to feed fires. The lowest pressure at which normoxia (PIO_2 = 149 mmHg) is maintained at 100% O_2 is 3.8 psia, however given the need to maintain a diluent gas at 30% ([V2 6002] Inert Diluent Gas) while maintaining normoxia and CO2 limits ([V2. 6004] Nominal Vehicle/Habitat Carbon Dioxide Levels), the lowest achievable cabin pressure is 5.0 psia (see Figure 6.2-1—Atmospheric Composition). Although mild hypoxia is allowed per [V2 6004], there is not sufficient rationale for mild hypoxia at the lower end of this pressure because the beneficial aspects of DCS mitigation have already been achieved and the materials flammability preferences have already been exceeded. Total pressure must be considered in conjunction with O_2 and CO_2 requirements. Under certain spacesuit operations (e.g., DCS treatment, leak checks), the crewmember may be exposed to pressure above or below this range for a limited period. *From: NASA-STD-3001 Volume 2, Rev D *Currently under consideration for NASA STD 3001 Volume 2, Rev D (not yet published)*

Background

Partial Pressure of Oxygen

- Oxygenation of tissues is one of the most important processes that take place within the human body. Oxygen feeds tissues and ensures metabolic processes and cellular functions take place. As crewmembers travel in space it is imperative to maintain the partial pressure of oxygen to keep crewmembers healthy and able to preform required functions.
- Partial pressure of oxygen considers oxygen in a dry gas environment. This does not accurately reflect the partial pressure available for diffusion within the alveoli of the lung and able to supply the body. When air is inhaled, it is warmed by the pulmonary tract and exposed to humidity/water vapor that affects the oxygen partial pressure called partial pressure of inspired oxygen (P_iO_2), as inhalation continues oxygen partial pressure is also affected by CO_2 during the alveolar gas exchange further decreasing oxygen referred to as alveolar partial pressure PAO_2.



Source: Ragdona et al 2020. See Reference List.

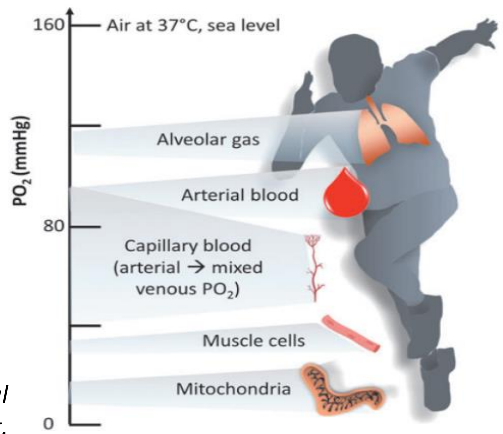
Partial Pressure of Oxygen (ppO_2) the percentage proportion of dry oxygen in air.

Partial Pressure of Inspired Oxygen (P_iO_2) the partial pressure of oxygen considering how the humidity (containing H_2O) of inspired air can change the air mixture percentages.

Alveolar Partial Pressure (PAO_2) the partial pressure of oxygen that fills the alveoli during inspiration, reduced from dry pressure by inspired humidity (H_2O) and mixing with end alveolar gas (CO_2) during alveolar air exchange.

ppO_2 = Pb X F_iO_2 (Pb is barometric pressure, F_iO_2 is a fraction of inspired oxygen assuming a dry gas condition).
P_iO_2 = (Pb – PH_2O) x F_iO_2 (PH_2O is partial pressure of H_2O), PH_2O is partial pressure of water introduced during inspiration.
PAO_2= (Pb – PH_2O) x F_iO_2 – ($PaCO_2$ x 1.25), PCO_2 is partial pressure of CO_2 introduced during alveolar gas exchange.
Example of inspired partial pressure at sea level: (Pb=760, PH_20=47mmHg, FiO_2 = .21 (21% of Atmospheric Atm)) PiO_2= (PB – PH_2O) x (FiO_2), 760mmHg-47mmHg x (.21)=149.7 mmHg

Partial pressure determines the availability of oxygen in lung tissues for dissolution into the blood, thus affecting the availability of blood oxygen to body tissues (see oxygen cascade below). Symptoms occur if partial pressure is not adequate to perfuse body tissues or support body functions.



Source: Burtscher et al 2022. See Reference List.

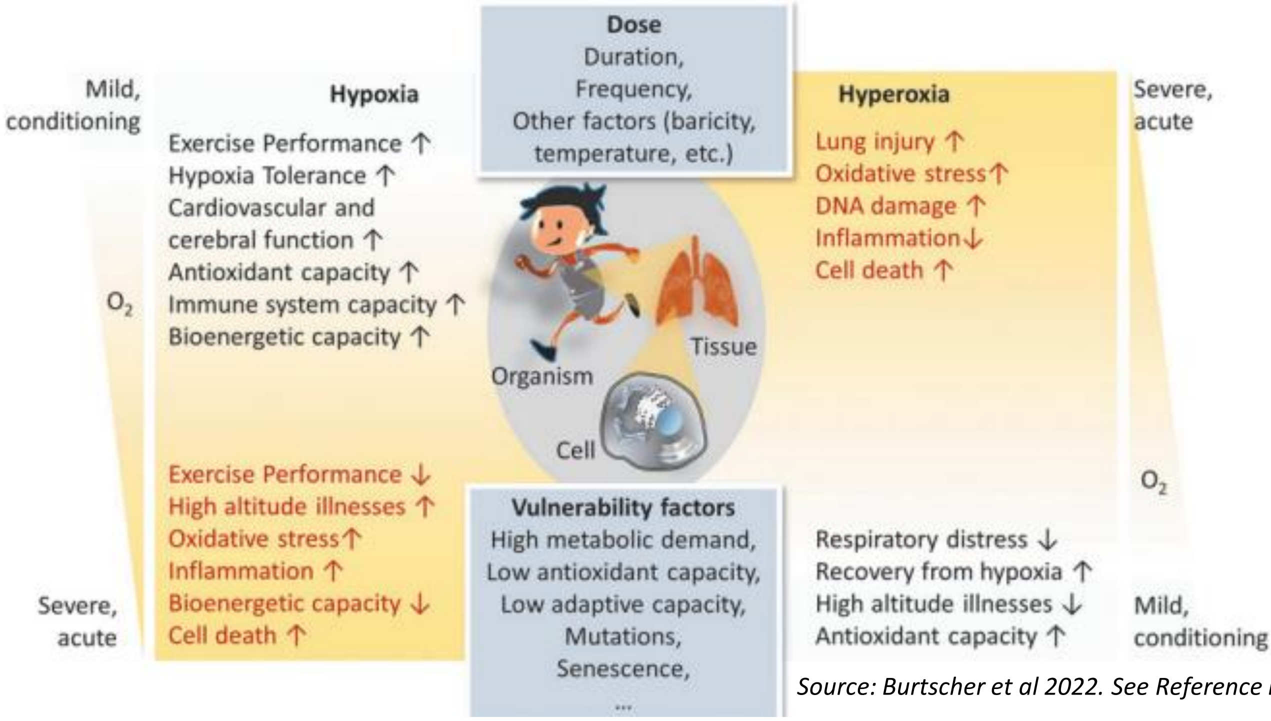
Background

Physiological Effects - Hypoxia

Acute hypoxia is associated with a variety of physical symptoms and decreases in ability to complete tasks. The onset and severity of hypoxia depends on factors including altitude, barometric pressure, and the O_2 content. In subjects with normal ventilation and gas exchange, the P_iO_2 in the lungs controls how much oxygen is delivered to the tissues.

Hypoxia occurs when Oxygen (O_2) is not sufficient to supply body tissues and maintain homeostasis.
Hyperoxia is a state of excess supply of O_2 in tissues and organs than normally exists.
Normoxia Sufficient oxygen is supplied to provide body homeostasis.

The balance of O_2 supply—energetic crisis versus oxygen toxicity



Source: Burtscher et al 2022. See Reference List.

Hypoxia-induced physiologic changes include:

- **CNS:** mental changes, at times undetectable to crew
- **Vision:** decreases in color, night, and peripheral vision
- **Nonspecific:** fatigue, nausea, headache, dizziness, mood alterations
- **Sleep:** decrease in quality
- **Breathing** : hyperventilation

See the OCHMO-TB-004 Carbon Dioxide (CO_2) for additional atmospheric information regarding CO_2 and other constituents.

Background

Physiological Effects– Hypoxia and Hyperoxia
Diagnosis and Treatment

One of the most difficult parts of treating hypoxia is being able to recognize symptoms and diagnose the problem. Hypoxia symptoms can be mistaken for fatigue or other causes and can be complicated with the fact that crew experiencing hypoxia may have loss of cognitive function and reasoning. It is important to prepare crewmembers with pre-flight hypoxia training which allows them to experience hypoxia (while being monitored) and to recognize their own symptoms. Crewmembers are also trained to monitor fellow crewmembers for symptoms as it may be easier to recognize symptoms in others.

High altitude chamber training *Source: NASA*

ISS crew have a portable O_2 analyzer (right) which can be used to monitor poorly ventilated areas and can be used when a crewmember exhibits hypoxia symptoms. *Source: NASA*

Hypoxia Treatment

Once diagnosed, the main treatment for hypoxia is to supply crew with supplemental oxygen to resolve the O_2 deficiency. Crewmembers can be trained to use quick don masks that provide additional O_2.

Hyperoxia breathing in high concentrations of O_2 can result in a decrease in ventilation and heart rate. In space, normobaric hyperoxia occurs when the O_2 has increased but metabolic requirements for O_2 have not. This can result in toxic oxygen levels, potentially leading to respiratory concerns or tissue-level injury.

Emergency quick don oxygen mask *Source: NASA*

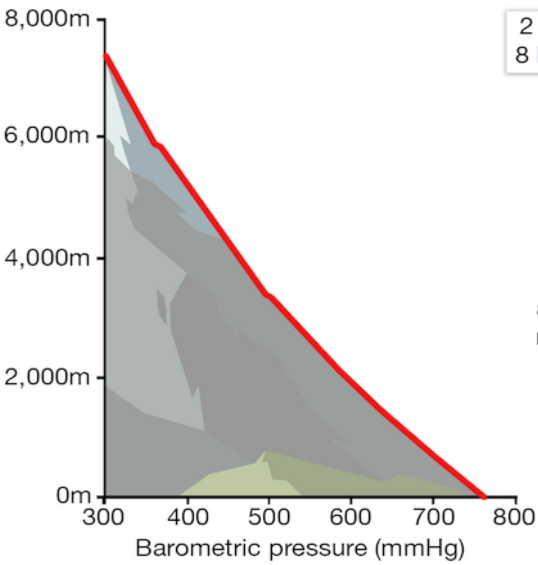
- Hyperoxia in space is usually encountered using different gas mixtures during various phases of the mission. For example, if crew encountered a contingency situation requiring a breathing apparatuses supplying 100% oxygen for a prolonged time, illness or injury may require crew to breathe supplemental O_2 for longer periods, or similar.
- Hyperoxia treatment primarily consists of reducing the partial pressure of oxygen in atmospheric gas and supportive care of any toxic sequelae. Toxic effects of hyperoxia can resolve quickly when crewmembers return to more appropriate atmospheric gas mixes.
- In addition to hyperoxia risk, increased percentage of oxygen in the atmospheric conditions significantly increases fire risk, posing potentially life-threatening conditions for the crew. See OCHMO-TB-008 Fire Protection for additional information.

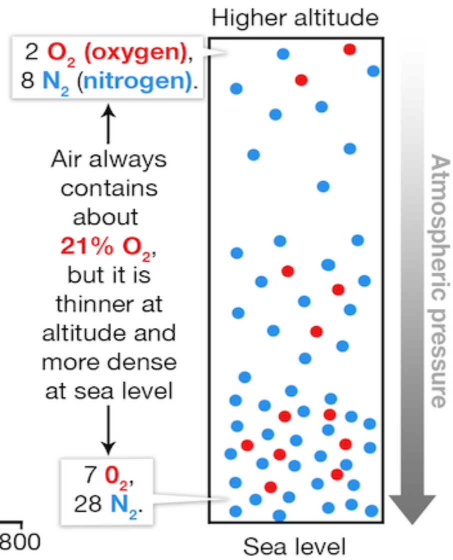
Background

Altitude, Humidity and Oxygen Partial Pressure

When creating the vehicle habitat, programs try to accommodate for equivalent altitude, pressure, and environmental (humidity) conditions to maintain the atmosphere as close as possible to sea level conditions.

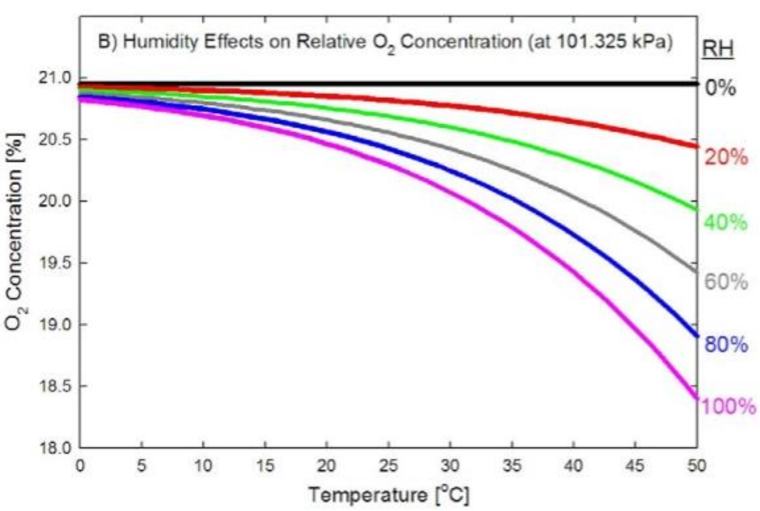
To maintain this, the vehicle has a pressure control system which monitors the total pressure as well as oxygen levels. As air pressure falls for example due to pressure vessel specification leakage or some contingency, the pressure control system will attempt to maintain the desired cabin pressure through the addition of air, nitrogen and/or oxygen. Dispersion of atmosphere gases change depending on the surrounding pressure/atmosphere conditions including altitude, barometric air pressure (Pb), and climate (temperature, relative humidity).





Altitude – as altitude increases air pressure decreases and oxygen partial pressure decreases.

Pressure – as air pressure decrease, gas molecules become less dense and have increased mobility.



Relative humidity – as humidity increases levels of water vapor increase and the partial pressures of oxygen decreases.

Temperature – alone does not affect oxygen partial pressures.

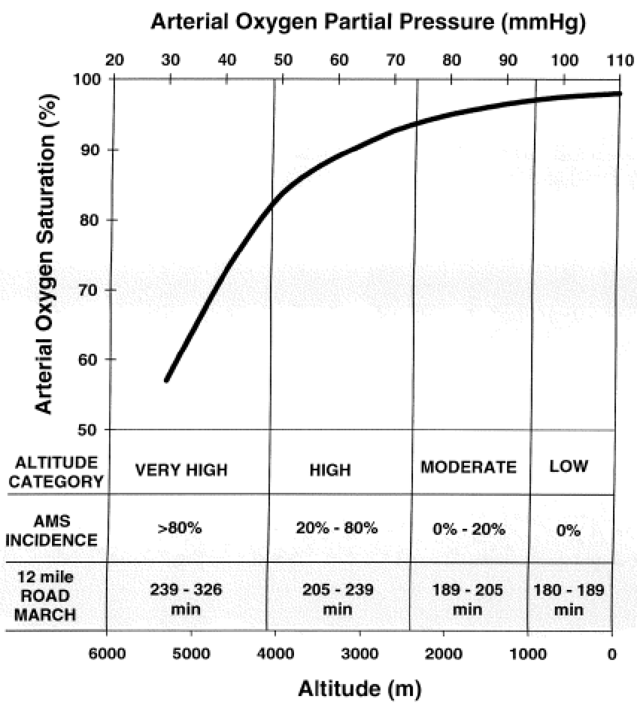
[V2 6022] Atmospheric Monitoring and Alerting Parameters The system **shall** alert the crew locally and remotely when atmospheric parameters, including atmospheric pressure, humidity, temperature, ppO_2, and $ppCO_2$ are outside safe limits. *From NASA-STD-3001 Volume 2, Rev C*

Background

Physiological Effects at Altitude and Partial Pressure

To better explain ranges for total and partial pressure, scientists relate the pressure environment to that which is experienced at a particular altitude, the equivalent air altitude (EAA), assuming similar physiological conditions between the identified pressures and altitudes. A significant concern with pressure or altitude, is symptoms associated with hypoxia that can interfere with crew comfort, health, and ability to execute tasks. These symptoms drive what pressure and oxygen values are best used for the cabin environment, and ultimately what pressures are tolerable for specific periods of time. Generally, the average person acclimated to sea level may begin to experience subtle decrements near PaO_2 of 80mmHg, (EAA 5,100 ft) and continue till loss of consciousness at 30mmHg (EAA 42,000 ft)[31]. Currently the ISS cabin pressure is typically maintained at 14.7 psia with 21% oxygen which is equivalent to sea level.

Source: Barrett et al Principles of Spaceflight Medicine



The relationship of decreased oxygen availability to altitude illness and performance decrements provides a classification of altitude exposure based on arterial oxygen content and physiologic effects. This graph (left) shows that with ascent of unacclimatized low altitude, residents ascending rapidly (<6 hours) to increasing altitudes risk developing altitude illness. Performance decrement is inversely related to partial pressure of oxygen. The physical work performance (road march left) begin to be decremented at altitudes > 1000m (3000 ft).

Left graph shows relationship between altitude, arterial oxygen partial pressure and arterial oxygen saturation in unacclimatized personnel. Categorizing altitudes is based on physiologic responses to hypoxia.

Source: U.S. Army Research Institute of Environmental Medicine 2004

10.3 ALTITUDE-PRESSURE TABLE

(1) Altitude m	(2) Altitude ft.	(3) Pa mm Hg	(4) (Pa—47) mm Hg	(5) .209 (Pa—47) mm Hg
0	0	760	713	149
610	2000	707	660	138
1220	4000	656	609	127
1830	6000	609	562	118
2440	8000	564	517	108
3050	10000	523	476	100
3660	12000	483	436	91
4270	14000	446	399	83

Source: W.G.Brombacher 1935

Altitude-Pressure Table: Relationship between Altitude and Pressure

(3) Pa = Barometric pressure

(4) (Pa-47) = (a) total pressure of dry gases after inspired gas saturated with water vapor at 37 degrees, (b) also equal to the inspired O_2 tension PiO_2 when pure oxygen inspired

(5) .209 (Pa-47) = inspired O_2 tension, PiO_2 when air is breathed

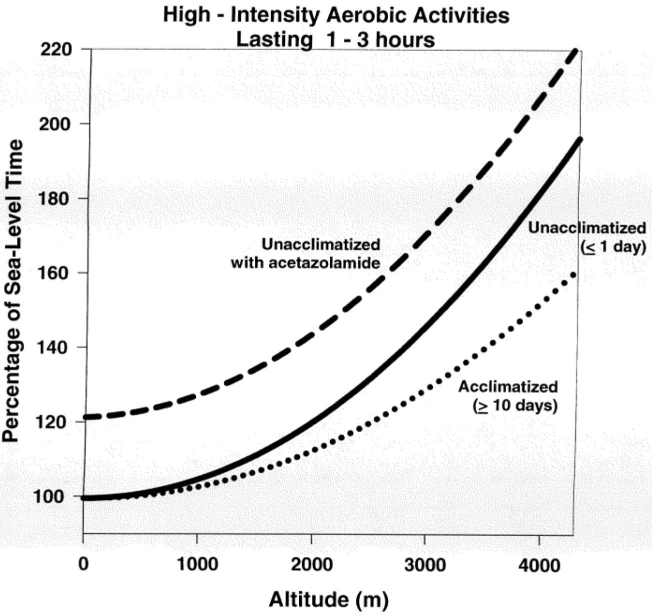
Background

Physiological Effects at Altitude and Partial Pressure
Spaceflight atmosphere experience is similar to the physical experience of ascending to increased altitudes; this data is considered (pressure equivalent at specific altitudes) to predict pressure effects during spaceflight. Below is an example of altitude effects on task completion as well as improvement upon 1 week acclimatization when exposed to various altitudes highlighting physiological affects of altitude travel.

ALTITUDE	% INCREASE IN TIME TO COMPLETE TASKS RELATIVE TO SEA LEVEL							
	Tasks < 2 min		Tasks 2 - 5 min		Tasks 10 -3 0 min		Tasks > 3 hrs	
	Initial	> 1 wk	Initial	> 1 wk	Initial	> 1 wk	Initial	> 1 wk
1,220 m (4,000 ft)	0	0	2	0	4	1	7	3
2,130 m (7,000 ft)	0	0	7	2	11	3	18	10
3,050 m (10,000 ft)	0	0	12	5	20	9	40	20
3,960 m (13,000 ft)	2	0	18	9	45	20	65	45
4,880 m (16,000 ft)	2	0	50	25	90	60	200	90

Source: Army Altitude Acclimatization Guide

US Army describes the rapid ascent of non-acclimatized persons to altitudes above 6000 ft increases risk of altitude illness and decreases physical and cognitive work performance. Altitude acclimatization training involving hypoxia exposure over time can decrease risk of performance decrements.



Hypoxia Can negatively affect senses, mood, psychomotor, and cognitive tasks beginning with dark adaptation vision beginning to be affected between 3000 and 4000 ft to mood and reaction time affected around 9000 ft.[32] Human physiology adapts upon high altitude and hypoxia exposure including plasma volume and red blood cell adjustment to better facilitate oxygen delivery. The decrements can improve with length of exposure and/or acclimatization training.

Pharmacology The medication Acetazolamide can assist with altitude prophylaxis and to decrease altitude symptoms. Acetazolamide induces metabolic acidosis and stimulates breathing and increases arterial oxygen to decrease hypoxia symptoms[32], however this has been associated with potential increased intracranial pressure and its use is currently under study.

Altitude-related Complications Rapid ascent without acclimatization can increase risk of serious complications.

Acute Mountain Sickness (AMS) Short lived (2-7 days) symptoms of headache, nausea, fatigue, and lightheadedness varies in severity, prior AMS history increases AMS risk.

High Altitude Pulmonary Edema (HAPE) Life threatening form of non cardiogenic pulmonary edema involving accumulation of fluid in lungs, worsens when rapid altitude ascent accompanied by exercise.

High Altitude Cerebral Edema (HACE) Life threatening swelling of the brain due to physiological effects of high-altitude including symptoms of disorientation, lethargy, and nausea.

Application

When designing a vehicle, to ensure crewmember well being, alterations in the partial pressure of O_2 are significant to crew experience. In addition to altitude and humidity influences, pressure may be lowered during spaceflight due to nominal cabin leakage, unplanned events, and during EVAs. When total pressure is lowered, partial pressure of oxygen is lowered, risk of hypoxia increases, and it may be necessary for the relative percent of available O_2 to be increased to sustain crew health.

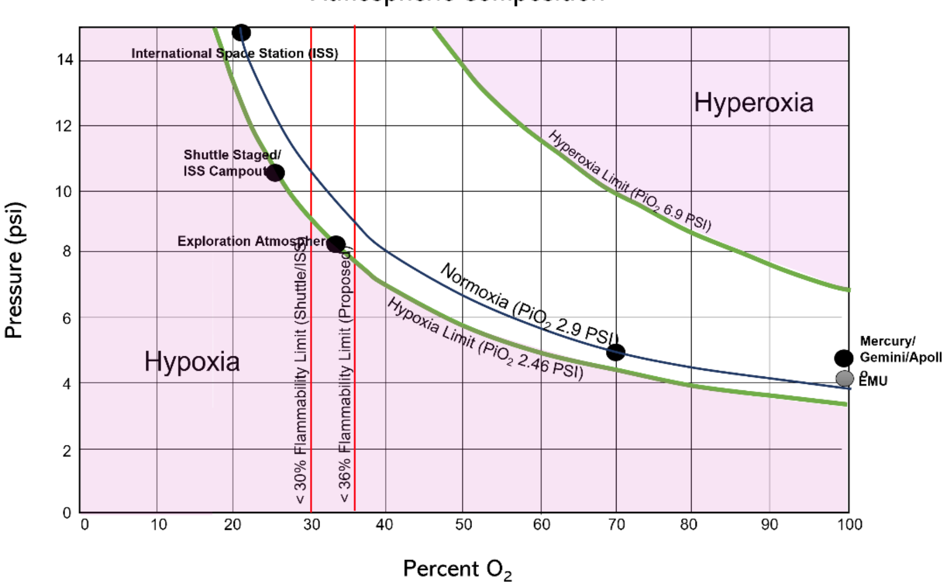
[V2 6003] O2 Partial Pressure Range for Crew Exposure The system **shall** maintain inspired oxygen partial pressure (PIO2) in accordance with Table 1, (below) Inspired Oxygen Partial Pressure Exposure Ranges. *From NASA-STD-3001 Volume 2, Rev C*

Table 1 – Inspired Oxygen Partial Pressure Exposure Ranges

Inspired O_2 partial pressure $P_IO_2 = (PB-47)*F_IO_2$	Normoxia Target Range	Indefinite Hyperoxia Upper Limit	Short-Term Hyperoxia Upper Limit	Mild Hypoxia Lower Limit
P_IO_2 (mmHg) $P_IO_2 = (PB-47)* F_IO_2$	145-155	356	791	127
P_IO_2 (psia)	2.80-3.00	6.89	15.30***	2.46
Acceptable Duration	Indefinite	Indefinite	6-9 Hours *	Indefinite with monitoring**
Examples	Habitat and Spacesuit Minimum	EVA and Cabin Depress In-Suit Survival	O_2 Prebreathe for EVA Preparation	EVA Preparation (ISS Campout, Shuttle 10.2, Exploration Atmosphere of 8.2 psia and 34% O_2)

From Johnson Procedural Requirements (JPR) 1830.6 (REQUIREMENTS APPLICABLE TO PERSONNEL PARTICIPATING IN DIVING, HYPER/HYPOBARIC CHAMBERS, AND PRESSURIZED SUIT OPERATIONS). Page 15, subsection 4.2: Limitations during Oxygen Breathing," shows the limits for prebreathe in a spacesuit. The limit is nine hours when that is the only exposure to enriched O2 in a 48-hour period. The limit is six hours when it is the only exposure to enriched O2 in a 24-hour period and also states that consecutive daily exposures are not to exceed five consecutive days. **There is no opportunity to collect data in microgravity with PIO2 of 127 mmHg to cover the durations of Exploration Class missions, so a health monitoring and mitigation plan are required to implement this condition ***This PIO2 may be exceeded during DCS treatment.** 1-hour time-weighted average with an absolute lower limit of 122 mmHg/2.36 psia*

Atmospheric Composition



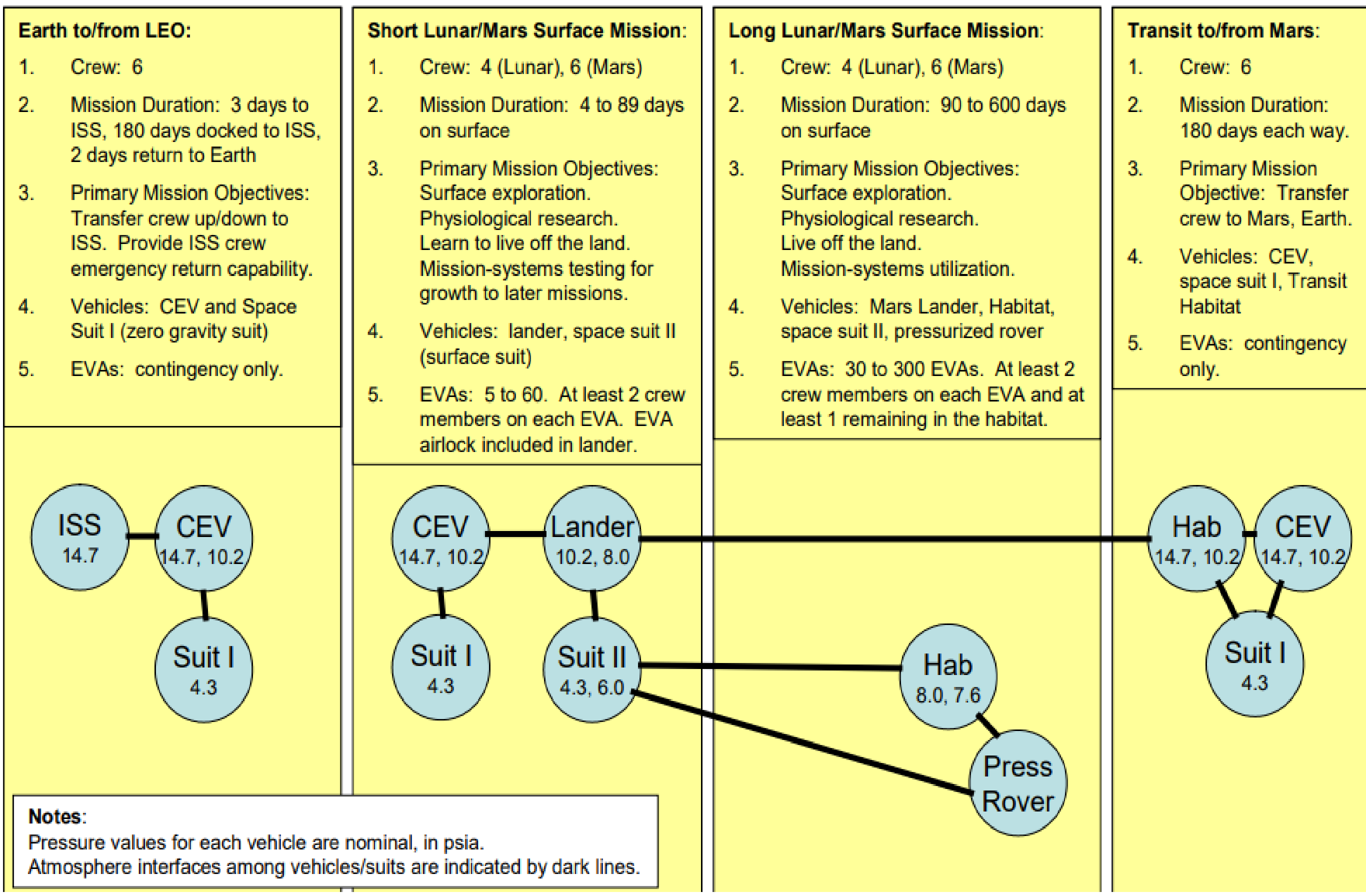
The graph represents the range of hypoxia, normoxia, and hyperoxia in various spaceflight vehicle baseline cabin environments and during extravehicular activities (EVAs) when considering barometric pressure. Additionally, the green vertical line marks the limit of O_2 content to prevent pulmonary atelectasis. This graph uses psia for pressure measurement.

Application

Pressure/Oxygen Challenges associated with mission pressure transitions

As missions evolve from Low Earth Orbit (LEO) to long duration, many atmospheric challenges and considerations will occur. Programs will have to plan, as they do for current EVAs, the best way to make the atmosphere/pressure transition while protecting the crewmembers and mission objectives. The image below is an example developed by NASA to plan for Constellation missions and shows the type of pressure transitions that can take place and need to be accounted for in future missions.

Cross Vehicle Atmosphere Considerations



Source: 2010 NASA EWAG Atmosphere Report

[V2 6007] Rate of Pressure Change For pressure changes >1.0 psi, the rate of change of total internal vehicle pressure **shall not** exceed 13.5 psi/min.
From: NASA-STD-3001 Volume 2, Rev C

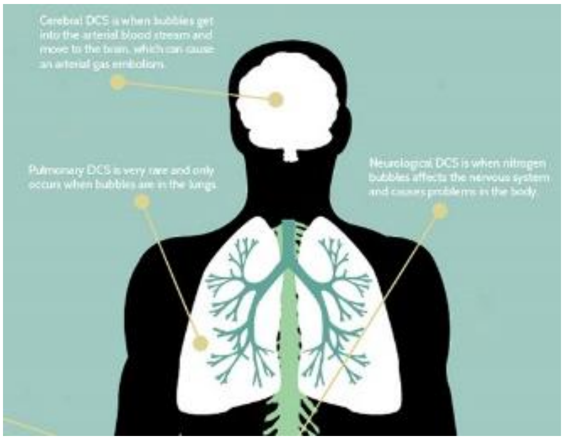
Background

Physiological Effects Decompression Sickness

Decompression Sickness (DCS) Rapid alterations in ambient pressure environments can lead to a series of illnesses or injuries, frequently from evolution of gases in body fluids. Decompression sickness is caused by the evolution of dissolved nitrogen into gaseous state, forming bubbles as pressure decreases.

Types of Decompression Sickness

- Type 1: joint pain, single extremity tingling or numbness, and mild skin symptoms.
- Type 2: central nervous system or cardiovascular symptoms. Symptoms can range from muscle weakness, confusion, impaired balance, and stroke. Injuries can be fatal.
- Gas emboli can be classified as venous gas emboli (VGE) or arterial gas emboli (AGE).
- The risk of DCS is can be raised by high levels of activity during exposure to altered pressure environments.



Example of Spaceflight-related Decompression: The ISS is pressurized to 14.7 psi, equivalent to the atmospheric pressure at sea level. During a spacewalk astronauts wear an EVA suit that is pressurized to 4.3 psi. If crewmembers did not take preventive actions, the large pressure transition when moving from the vehicle to an EVA suit could lead to nitrogen evolution in the body. Bubble formation could cause physical pain (joint nitrogen displacement), and physical structural damage if lodged into the cerebral or pulmonary circulation.

- To prevent DCS, NASA crewmembers complete a prebreathe protocol, including breathing oxygen-rich air to flush out body nitrogen prior to EVA. This helps prevent nitrogen evolution and development of bubbles.
- If DCS occurs, current treatment options include recompression to sea level pressure or higher (hyperbaric therapy), breathing 100% O_2, and supportive care of any injuries or sequelae.
- When DCS symptoms occur in space, returning to normal cabin environments may be enough to resolve symptoms. Alternatively, use of the cabin or even an EVA suit to raise ambient pressure to hyperbaric conditions may be considered.

See the Decompression Sickness (DCS) OCHMO Technical Brief for additional atmospheric information regarding DCS.

Background

Physiological Effects of Barotrauma

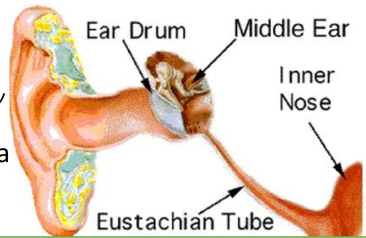
Barotrauma is injury to your body caused by changes in barometric (air) or water pressure. This most often occurs when people travel to high altitudes or dive underwater, but additionally can occur for crew when traveling in space.

- Barotrauma is most often experienced in the ear and sinuses but is also experienced in the lungs or other major organs. Barotrauma injuries can cause pain or, in severe cases, can be life threatening.
- Barotrauma is caused by pressure changes between ambient pressure and the pressure of gases trapped within closed spaces in the body.
- Injury occurs when the change in ambient pressure overcomes the capacity of the enclosed space to equalize. Injury is more common when the trapped gas pressures are lower than the ambient pressure, but positive pressure injuries have also been reported.

Examples of Barotrauma Ear/Sinus squeeze: failure to equalize pressure of trapped gas in the middle ear or sinuses cause pain, bleeding, or irritation of mucosa. Teeth (dental squeeze): expansion of gas within a tooth causes pain, fracture, or other injury. Lung: rapid expansion of tissue gas can cause pneumothorax or pulmonary tissue injury, can lead to arterial gas embolism.

Pulmonary Barotrauma (left) *Source: YouTube Respiratory Therapy Zone*

Ear Barotrauma (right) *Source: NASA*



Tympanic membrane rupture *Source: NASA*

[V2 6150] Barotrauma Prevention During a commanded pressure change, the system **shall** pause within 1 psi of the pause command being issued by the unsuited or suited crewmember, with ability to increase or decrease pressure as needed after the pause. *From: NASA-STD-3001 Volume 2, Rev C*

Barotrauma in Space

- Changes in pressure occur during space flight missions when the crewmember is transferring between habitable volumes of differing pressures, for example when going from vehicle atmosphere to Extravehicular Activity (EVA) suit.
- Future missions potentially involve additional pressure change scenarios. For example, a lunar sortie mission scenario may include several circumstances where pressure is expected to change including transfers between a pressurized habitat, a pressurized rover, and pressurized suit.
- Other scenarios may involve unplanned contingencies i.e., damage to the vehicle causing unintended pressure changes.

Valsalva maneuver
Source: Wikipedia

Underwater crew pressure training
Source: NASA

Prevention includes gradually controlled pressure changes, crew training in equalizing techniques, and pharmaceuticals including decongestants, pain medication and supplemental or supportive care when required.

Application

Partial Pressure Extravehicular Activities (EVA) Considerations

EVAs introduce many new challenges to the atmospheric pressure and oxygen balance:

- When crewmembers prepare for an EVA, they move from the cabin atmosphere to a space suit pressurized at much lower pressure. A too-rapid pressure transition can increase the risk of DCS.
- The EVA preparation time must be minimized to accommodate the overall mission objectives and timeline.
- Crewmembers will complete a schedule challenging prebreathe protocol which involves oxygen either via mask or in-suit to flush Nitrogen from the body decreasing risk of DCS.
- 100% O_2 environment introduces increased risk of flammability, thus imposing a requirement to maintain ppO_2 below the cabin flammability limit while conducting mask prebreathe.
- For long duration flights a variety of pressure transitions are possible within the mission based on lander, rover, EVA, and lunar or planetary surface activities.

Alternative EVA Preparation Atmosphere Conditions

To optimize the EVA preparation, NASA is studying options including changing the cabin pressure/oxygen balance, allowing for less cabin to suit pressure transition and shorter prebreathe times. See table below:

Pressure (psia)	%O_2	P_IO_2 (mmHg)	Equivalent Air Altitude (ft)*	Isohypoxic Altitude (ft)**	Pressure Altitude (ft)	Comment
8.2	34	128	4000	8300	15700	Exploration Atmosphere (EA)
9.8	28	128	4000	6600	11200	Option for Alternate EA
10.2	26.5	127	4150	6300	10100	Shuttle/Campout Atmosphere (SC)

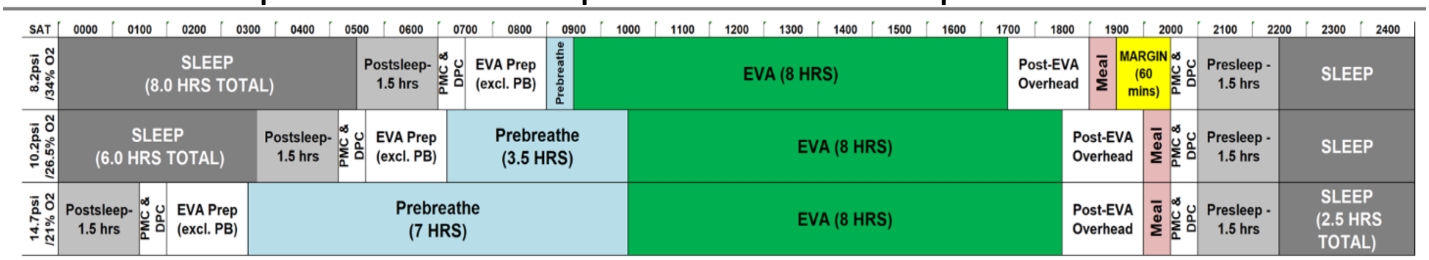
Advantages:

- Shorter prebreathe times allow crewmembers more time for rest and other mission activities
- Wessel Study 2018 showed exposure to mildly hypoxic environment did not show mission limiting events, or effects carrying significant long term health consequences. No additional symptom reports related to mild hypoxia in microgravity on shuttle Equivalent Air Altitude of 4,000 feet was not more provocative than sea level.

Concerns:

- The oxygen environment introduces a mildly hypoxic environment which although it is well tolerated on earth, when in combination with microgravity there is a concern that the synergistic effects are unknown and have potential to adversely affect health and performance. For example, the acute change in ppO_2 from normoxic to potentially hypoxic can result in AMS symptoms including headache, nausea, dizziness or fatigue which could potentially affect performance.
- Flammability risks must always be factored in when considering higher percent oxygen.

Example of Prebreathe atmosphere environments and equivalent Air Altitudes



Source: NASA

Reference Data

Atmosphere Pressure History

A variety of atmospheric conditions have been developed and operated to meet vehicle and spacesuit needs. The atmospheres have ranged from low-pressure, pure O_2 environment (Mercury, Gemini, and Apollo), to the space shuttle and current ISS Earth sea-level pressure and O_2 content (14.7 psia/21% O_2). Apollo preflight checkout procedures initially encompassed an over-pressurization of the Command Module (CM) using 100% O_2. After the Apollo I fire, ground procedures were modified and a mixture of 60% oxygen and 40% nitrogen was used to reduce the fire hazard.[14]

Table 1. Past and Present Spacecraft Cabin Atmospheres

Program	Nominal Cabin Pressure, psia	Nominal Cabin O_2 Concentration, Volume %	EVA Suit Pressure, psia	EVA O_2 Prebreathe Time, minutes	EVA Prebreathe Conditions
Mercury	5	100	-	-	-
Gemini/Apollo	5	100	3.75	0	-
Skylab	5	70	3.75	-	-
Shuttle	10.2	26.5	4.3	40	In-suit after 36 hours at 10.2 psia
	14.7	21	4.3	240	In-suit
ISS/United States	14.7	21	4.3	120-140	Mask and in-suit; staged with exercise
				240	In-suit
Salyut, Mir, ISS/Russia	14.7	21	5.8	30	In-suit
Commercial Crew Program (CCP)	14.7	21	N/A	N/A	N/A
MPCV CM	10.2 - 14.7 for Gateway Operations	21 – 26.5	4.3 – 8.1 psid to cabin	Scenario-dependent	In-suit
	10.2 for Lunar Lander Operations	26.5			

Source: Lange et al. (2005) summarized previous NASA spacecraft atmosphere designs and operations, as shown in Table 2 References: Carson, et al. (1975), McBarron, et al. (1993), Waligora, et al. (1993), NASA (2002), NASA (2003). (1) 100% oxygen. (2) In earlier versions of the Orlan suit, the pressure could be reduced to 26.5 kPa (3.8 psia) for short-duration work regime. (3) Under emergency conditions, a minimum of 150 minutes of unbroken prebreathe is recommended. *Source: EAWG Report 2010. NESC Document #: NESC-RP-20-01610*

Development of Atmosphere Recommendations:

The Exploration Atmospheres Working Group (EAWG) was tasked by NASA to generate recommendations on characteristics of internal atmospheres for exploration spacecraft, including suits and planetary exploration vehicles

- Three EAWG subgroups: physiological and medical, mission operations, and vehicle and habitat systems, were formed to focus on specific risk areas.
- Analytical methods were combined to form systems engineering process. White papers were generated by EAWG members and NASA personnel to provide explanations of technical and design challenges.
- This group ultimately identified selection and validation of exploration spacecraft atmospheres.
- EAWG developed the *Final Report of Recommendations for Exploration Spacecraft Internal Atmospheres (2010)*.
- EAWG developed *Effects of the 8 psia/32% O_2 Atmosphere on the Human in the spaceflight Environment (2013)* report which gave atmosphere recommendations including EVA considerations.

Source: EAWG Atmosphere Report 2010

Lessons Learned

Acute Depressurization of Soyuz 11

A tragic mishap involving acute depressurization occurred on a Russian Soyouz vehicle on June 29,1971. Cosmonauts Georgy Dobrovolsky, Vladislav Volkov, and Viktor Patsayev were returning from a successful mission as the first humans to crew a space station, the Salyut 1. Their mission involved multiple science experiments to determine the effects of space during the longest human endurance space mission to date. During reentry, the crewmembers did not wear spacesuits as this was felt at the time to be redundant in a pressurized vehicle environment. However, on descent, radio communications abruptly ended well before expected loss of signal; after landing, recovery personnel opened the hatch to find all crewmembers had perished. Resuscitation was attempted but was unsuccessful. The resulting investigation determined that vibrations occurring during jettison of the orbital module caused a pressure equalization valve to release a seal at approximately 168 km altitude rather than the nominal 4km opening altitude. This caused crew to be exposed to near-vacuum conditions, leading to loss of consciousness and severe decompression sickness including ebullism, the spontaneous evolution of body fluids to gaseous state. Resulting injuries were fatal. Following this tragic event, multiple design changes were made and the use of pressure suits for dynamic operational activities (including launch and reentry) became common to provide improved protection from sudden changes in vehicular pressure.

Cosmonauts Georgy Dobrovolsky, Vladislav Volkov, and Viktor Patsayev
Source: NASA

Memorial to the lost cosmonauts of Soyuz 11
Source: NASA

Refer to the Entry Landing Mishaps and Decompression and LEA Suit Mishaps OCHMO Technical Briefs for additional information.

Back-Up

Referenced Technical Requirements

NASA-STD-3001 Volume 1 Revision B
[V1 3003] In-Mission Preventive Health Care All programs shall provide training, in-mission capabilities, and resources to monitor physiological and psychosocial well-being and enable delivery of in-mission preventive health care, based on epidemiological evidence-based probabilistic risk assessment (PRA) that takes into account the needs and limitations of each specific design reference mission (DRM), and parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more. The term "in-mission" covers all phases of the mission, from launch, through landing on a planetary body and all surface activities entailed, up to landing back on Earth. In-mission preventive care includes, but is not limited to: (see NASA-STD-3001, Volume 1 Rev B for full standard).
[V1 3004] In-Mission Medical Care All programs shall provide training, in-mission medical capabilities, and resources to diagnose and treat potential medical conditions based on epidemiological evidence-based PRA, clinical practice guidelines and expertise, historical review, mission parameters, and vehicle-derived limitations. These analyses should consider the needs and limitations of each specific DRM and vehicles. The term "in-mission" covers all phases of the mission, from launch, through landing on a planetary body and all surface activities entailed, up to landing back on Earth. In-mission capabilities (including hardware and software), resources (including consumables), and training to enable in-mission medical care, are to include, but are not limited to: (see NASA-STD-3001, Volume 1 Rev B for full standard).

NASA-STD-3001 Volume 2 Revision C
[V2 6002] Inert Diluent Gas Cabin atmospheric composition shall contain at least 30% diluent gas (assuming balance oxygen).
***[V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure** The system shall maintain the pressure to which the crew is exposed to between 34.5 kPa < pressure ≤ 103 kPa (5.0 psia < pressure ≤ 15.0 psia) for indefinite human exposure without measurable impairments to health or performance.
[V2 6007] Rate of Pressure Change For pressure changes >1.0 psi, the rate of change of total internal vehicle pressure shall not exceed 13.5 psi/min.
[V2 6008] Decompression Sickness (DCS) Risk Identification Each program shall define mission unique DCS mitigation strategies to achieve the level of acceptable risk of DCS as defined below within 95% statistical confidence:
a. DCS ≤ 15% (includes Type I or isolated cutis marmorata).
b. Grade IV venous gas emboli (VGE) ≤ 20%.
c. Prevent Type II DCS.
[V2 6009] Decompression Sickness Treatment Capability The system shall provide DCS treatment capability.
[V2 9053] Protective Equipment Protective Equipment shall be provided to protect the crew from expected hazards.

**Currently under consideration for NASA STD 3001 Volume 2, Rev D (not yet published)*

Referenced Technical Requirements

[V2 11032] LEA Suited Decompression Sickness Prevention Capability LEA spacesuits shall be capable of operating at sufficient pressure to protect against Type II decompression sickness in the event of a cabin depressurization.

[V2 11100] Pressure Suits for Protection from Cabin Depressurization The system shall provide the capability for crewmembers to wear pressure suits for sufficient duration during launch, entry, descent (to/from Earth, or other celestial body) and any operation deemed high risk for loss of crew life due to loss of cabin pressurization (such as in mission dockings, operations during periods of high incidence of Micrometeoroids and Orbital Debris (MMOD) or complex vehicle maneuvers).

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